Integrating imaging modalities: what makes sense from a workflow perspective?

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Abstract: PURPOSE: From a workflow/cost perspective integrated imaging is not an obvious solution. An analysis of scanning costs as a function of system cost and relevant imaging times is presented. This analysis ignores potential clinical advantages of integrated imaging. METHODS: An analysis comparing separate vs integrated imaging costs was performed by deriving pertinent equations and using reasonable cost numbers for imaging devices and systems, room and other variable costs. Integrated systems were divided into those sequentially and simultaneously. Sequential scanning can be done with two devices placed in a single or in two different scanning rooms. Graphs were derived which represent the cost difference between integrated imaging system options and their separate counterparts vs scanning time on one of the devices and cost ratio of an integrated system and its counterpart of separate devices. RESULTS: Integrated systems are favoured by the fact that patients have to be up- and downloaded only once. If imaging times become longer than patient changing times, imaging on separate devices is advantageous. An integrated imaging cost advantage is achieved if the integrated systems typically and overall cost three fourths or less of the separate systems. If PET imaging takes 15 min or less, PET/CT imaging costs less than separate PET and CT imaging, while this time is below 5 min for SPECT/CT. A two-room integrated system has the added advantage that patient download time is not cost relevant, when imaging times on the two devices differ by more than the patient download time. CONCLUSION: PET/CT scanning is a cost-effective implementation of an integrated system unlike most current SPECT/CT systems. Integration of two devices in two rooms by a shuttle seems the way how to make PET/MR cost-effective and may well also be a design option for SPECT/CT systems.

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SPECIAL CONTRIBUTION

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Keywords Imaging system integration · Hybrid imaging · Cost-effectiveness · PET/MRI

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Introduction

Integrated imaging in the form of PET/CT has virtually replaced PET alone, and integrated SPECT/CT is replacing SPECT in many institutions. Recently, there has been a surging interest in PET/MR and some experimental systems are available. In principle any combination of cross-sectional imaging devices into an integrated system is of interest. However, the added value of the integrated system depends on several factors. The following factors support imaging system integration:

1. The devices which are combined in an integrated system complement each other technically and/or clinically.
2. The inherent match of the acquired images has substantial advantages over software fusion of images acquired on separate devices.
3. The clinical workflow is improved by system integration.
4. The integrated system has financial advantages over separate systems, i.e. it is more cost-effective.

Since the early days of PET/CT ample evidence has accumulated that PET/CT is synergistic as CT provides anatomical information lacking on PET images, and CT provides a fast way to correct PET images for photon attenuation [1]. Similarly, the increasing number of SPECT/CT systems suggests that synergy exists when integrating SPECT and CT systems [2]. Criterion 2 appears to be true for most body imaging with PET/CT and SPECT/CT [3], whereas software fusion might be sufficient for brain or heart imaging [4, 5].

The perspectives are similar for PET/MR and SPECT/MR integration with the difference that concepts and experimental systems exist in which full system integration allows simultaneous acquisition of nuclear and MR data [6, 7]. In body imaging, integration of PET and MR may make sense clinically as the information obtained is largely complementary like in PET/CT. Furthermore, simultaneous PET (or SPECT) and MR acquisitions in a fully integrated system may allow the measurements of different functional parameters at the same time. However, such systems are likely to be costly [8] and there is currently no straightforward way to use MR data for attenuation correction of emission scans [9]. Thus, the advantage of PET/MR integration is still subject to debate.

Whether and when an integrated imaging system makes sense from a workflow and financial perspective has not been analysed rigorously to our knowledge. Workflow and financial aspects are closely linked, and it is the purpose of this paper to give a simple analysis of the financial and workflow conditions under which imaging system integration may make sense.

Materials and methods

A simple cost model was devised and fed with realistic data on imaging times, patient changing times, yearly throughput and running costs of imaging systems. The assumptions may vary from country to country, but the corresponding Excel file can be adjusted easily to investigate how workflow and costs affect whether separate or integrated imaging makes sense. Graphs demonstrating the influence of varying imaging times as well as the relative cost of separate vs integrated systems on the cost difference between integrated and separate imaging are presented.

Types of systems considered

Equations for imaging times and costs for SPECT, PET, CT and MRI are set up. We will call integrated systems: *systems* and single systems: *devices*. Imaging device integration can be accomplished in several ways [10]. We distinguish the following configurations which are summarized in Table 1.

(I) Separate imaging systems which consist of two independently operating devices in separate rooms, where integration is accomplished by software.

(II) Sequential systems which consist of two devices with a shared shuttle system. The patient is shuttled from one to the other device without changing his position on the table. The two devices may be located in a single room as in current PET/CT and SPECT/CT systems, called IIa systems, or in two separate rooms, which we call IIb systems.

(III) Simultaneous systems which consist of two fully integrated devices that are able to acquire data simultaneously. An example is the experimental PET/MR system which combines a standard MR with a “head insert” PET device [7].

There are two important aspects which have to be noted. First, sequential PET/MR systems (type II systems) will require longer shuttling distances of 3–6 m than current PET/CT and SPECT/CT systems, where shuttling distances are typically 60 cm. This is due to the technical incompatibility of current PET and MR scanners. Second, type III PET/CT and SPECT/CT systems are also conceivable. In such systems the detectors of X-rays and gamma rays would have to be the same and the rays coming from the CT and the nuclear examination would have to be separated by a discrimination of the ray energy [11]. The major problem with type III whole-body systems in general is that their construction will likely require very high reengineering investments. These investments may be justified by the advantages of simultaneous data acquisition, but only when PET/MR will prove that it has unique clinical applications making it much superior to PET/CT. Data to prove this are currently not available.

In order to simplify our workflow and cost analysis the following assumptions are made:

1. Patients considered are only those who need two examinations, e.g. a PET and a CT.

Table 1 System configurations compared in workflow analysis

System type	Deployment	Patient transfer
Separate devices (I)	Two rooms	Patient moves himself on and off table
Sequential imaging system (IIa)	One room	Simple shuttle such as common table; no patient movement
Sequential imaging system (IIb)	Two rooms	Expensive shuttle system; no patient movement
Simultaneous imaging system (III)	One room	Common table; no patient movement

2. The entire process of imaging a patient consists of uploading a patient onto the table of an imaging device or system, performing the acquisition and then downloading the patient again from the imaging device or system. For simplicity's sake we assume that the time *Tc* it takes to upload and download the patient is equal for the imaging devices considered, while in reality setting up the patient for an MR examination with various surface coils may take longer than setting up a patient e.g. for a PET scan. Reasonable estimates for *Tc* are in the range of 10–15 min as measured in our service.
3. For shuttle systems (type IIb sequential systems) the transfer time of a patient from one to the other imaging device is considered negligible compared to the patient up- and download time *Tc*. This is realistic as in PET/CT and SPECT/CT the transfer time between imaging device A and B is a few seconds and corresponds to advancing the patient table by some 60 cm. In PET/MR systems, this may be more 1–3 min, which is still small compared to a *Tc* of 10–15 min.
4. An average imaging time is assumed per device type. This may obviously differ if an institution runs only head, cardiac or partial body scans.

Using these assumptions the total imaging time required to perform examinations on a device A and device B on a patient in type I, II and III systems can be set up. The notation is as follows:

– *Ta* and *Tb* imaging times on devices A and B
– *Tc* total up- and download time for patient per device
– *TL*=max (*Ta*;*Tb*), i.e. the longer of both device imaging times

$$\text{Separate (I)} \quad \mathrm{Tsep} = (\mathrm{Ta} + \mathrm{Tc}) + (\mathrm{Tb} + \mathrm{Tc}) = \mathrm{Ta} + \mathrm{Tb} + 2\mathrm{Tc}. \tag{1a}$$

$$\text{Sequential (II)} \quad \mathrm{Tseq} = \mathrm{Ta} + \mathrm{Tb} + \mathrm{Tc} \tag{1b}$$

$$\text{Simultaneous (III)} \quad \mathrm{Tsim} = \mathrm{TL} + \mathrm{Tc} \text{ with } \mathrm{TL} = \max\,(\mathrm{Ta}; \mathrm{Tb}) \tag{1c}$$

If a patient has to undergo both imaging examinations A and B, the most time efficient way to do this from a workflow perspective is in a simultaneous imaging system (type III): one imaging device is used full time for measuring, while the faster imaging device is idling for time |*Ta-Tb*|. Integrated type II or III systems have the advantage that the patient has to be placed and taken off the table only once compared to type I systems (cf. Eq. 1a vs Eqs. 1b and 1c).

With sequential type IIa systems, where both systems are in the same room, one imaging device is always idle while the other is running as two patients cannot be scanned in the two devices at the same time. However, for separate devices and sequential systems consisting of two devices in separate rooms connected by a shuttle, device A can be used for a second patient once the first patient is shuttled to device B. So, intuitively, type IIb systems with similar device acquisition times will approach the imaging time of type III systems if run in a "pipelined" fashion.

Calculation of imaging costs per minute

The above equations describe the times relevant for workflow, but they do not render the proper picture, because whether an integrated system set-up is preferable or not depends on the system cost per minute. In order to obtain imaging cost, we need to calculate the cost per minute per scanner and rewrite the above equations as cost equations. The following assumptions are applied in addition to those stated above:

5. The personnel cost per scan is considered constant independent of the scanning time and thus a fixed cost. This is reasonable because physician and administration costs only depend on the number of scans done and not on their duration, and most technician work is also proportional to the number of patients scanned.
6. The personnel cost is assumed to be the same independent of whether the patient is scanned on separate devices or integrated systems. This assumption is not fully correct, because running an integrated system may require somewhat less personnel than running two separate devices.

The cost of an imaging system has fixed and variable cost components. Relevant variable costs for a single imaging examination are the depreciation time over which an imaging system and the building have to be amortized and the annual interest rate of the capital cost. These in turn depend on the cost of the devices or systems. Other relevant variable costs for an examination are the annual cost of the service contract, the cost for annual upgrades and the cost to maintain the infrastructure (heating, electricity, cleaning). These variable costs per scan are importantly determined by the average length of a scan and the operating hours per year. Realistic assumptions have been made in Table 2 for these parameters. Note that we have not adjusted the operating hours of CT and MR scanners to the lower ones for PET and SPECT systems. This is admissible, because integrated systems can be run as CT and MR scanners during the hours when no radiopharmaceuticals are available.

Costs for each scan also include fixed costs mainly consisting of personnel costs and disposables. With the

Table 2 Cost assumptions for the analysed cross-sectional imaging systems in euros

Amortization and interest									
Depreciation time of equipment	Years	8							
Depreciation time of building	Years	20							
Annual interest rate		0.05							
Investment costs	PET	SPECT	CT	MR	PET/CT	SPECT/CT	PET/MR	PET/MR	PET(/CT)/MR
							Full integrat.	Same room	Different room
Scanner	1,200,000	500,000	1,000,000	1,300,000	1,600,000	1,200,000	2,800,000	2,400,000	2,800,000
Building	1,400,000	1,200,000	1,400,000	1,400,000	1,500,000	1,400,000	1,500,000	1,500,000	2,400,000
Fixed costs									
Scanner amortization	150,000	62,500	125,000	162,500	200,000	150,000	350,000	300,000	350,000
Capital cost	30,000	12,500	25,000	32,500	40,000	30,000	70,000	60,000	70,000
Building amortization	70,000	60,000	70,000	70,000	75,000	70,000	75,000	75,000	120,000
Building capital cost	35,000	30,000	35,000	35,000	37,500	35,000	37,500	37,500	60,000
Service contract	90,000	40,000	110,000	90,000	150,000	130,000	170,000	170,000	170,000
Upgrades	30,000	20,000	30,000	30,000	40,000	40,000	50,000	50,000	50,000
Infrastructural cost	35,000	30,000	35,000	35,000	40,000	40,000	55,000	55,000	55,000
Total fixed costs	440,000	255,000	430,000	455,000	582,500	495,000	807,500	747,500	875,000
Operating hours/year	1,920	1,920	2,400	2,400	1,920	1,920	1,920	1,920	1,920
Total fixed costs per scanning min	3.82	2.21	2.99	3.16	5.06	4.30	7.01	6.49	7.60

simplification made above under point 6, these costs for an integrated system will just be the sum of the same costs of the separate systems. Thus, when comparing the total imaging cost of integrated vs separate systems, the costs which are fixed for each scan and consisting mainly of personnel can be ignored.

All cost assumptions may vary from country to country, but can easily be adjusted by entering the local estimates into the grey fields of the Excel sheet corresponding to Table 2.

Calculation of imaging costs per study

The costs per scan (excluding the fixed costs which will not be relevant in this analysis as per points 5 and 6 above) can be obtained as the product of the total scan time and the costs per minute. The following equations then describe the total imaging costs per patient *Ca*, *Cb*, *Csep*, *Cseq* and *Csim* of the independent systems A and B and of type I, II and III integrated systems, respectively. *ca*, *cb* and *cab* represent the variable costs for independent systems A and B and the integrated system AB per minute.

$$\text{Independent device A} \quad \mathrm{Ca} = \mathrm{ca}^*(\mathrm{Ta}+\mathrm{Tc}) \tag{2a}$$

$$\text{Independent device B} \quad \mathrm{Cb} = \mathrm{cb}^*(\mathrm{Tb}+\mathrm{Tc}) \tag{2b}$$

The cost of scanning the patient with the two separate devices is just the sum of Eqs. 2a and 2b:

$$\begin{array}{ll}\text{Type I system} & \mathrm{Csep} = \mathrm{ca}^*(\mathrm{Ta}+\mathrm{Tc}) + \mathrm{cb}^*(\mathrm{Tb}+\mathrm{Tc}) \\ \text{(separate)} & \end{array} \tag{2c}$$

The cost of scanning the patient with a sequential system (type IIa) is given by

$$\begin{array}{ll}\text{Type IIa system} & \mathrm{Cseq} = \mathrm{cab}^*(\mathrm{Ta}+\mathrm{Tb}+\mathrm{Tc}) \\ \text{(sequential, same room)} & \end{array} \tag{2d}$$

wherein the cost per minute *cab* is multiplied by the total time used to scan, upload and download the patient.

The cost of scanning a patient in a simultaneous type III system is given by:

$$\begin{array}{ll}\text{Type III system} & \mathrm{Csim} = \mathrm{cab}^*(\mathrm{TL}+\mathrm{Tc}) \\ \left(\begin{array}{l}\text{fully integrated simultaneous system;} \\ \text{TL is the larger of Ta and Tb}\end{array}\right) & \end{array} \tag{2e}$$

Type III systems are more efficient than type IIa systems because imaging with both devices can occur simultaneously.

We have not yet discussed type IIb systems. On these systems an interesting imaging strategy can be used, which is more efficient than when the devices are placed in the same room. With proper hardware arrangements, device A can already be used again to scan a second patient when device B scans the first patient. As this set-up is like having two independent devices plus a patient shuttle, the total minute cost of the system is given by *ca* + *cb* + *cs*, where *cs* is the shuttle cost per minute. In the most efficient mode of such a system, the device using longer to scan is always running, while the other one is idle during a part of the acquisition time of the longer scan. The scanning cost *Cseqeff* is then given by the equation:

$$\begin{array}{l}\text{Type IIb system Cseqeff} = (\mathrm{ca}+\mathrm{cb}+\mathrm{cs})^*\mathrm{TX}; \\ \text{(devices in separate rooms connected by a shuttle)}\end{array} \tag{2f}$$

The meaning of *TX* is explained below. For the required efficient shuttle system an increase of scanner cost by 300,000 euros was assumed, translating into a *cs* = 0.39 euros/min.

TX is the effective occupancy of the integrated system and is different for different imaging time regimes

1. *Ta* = *Tb*. In this case, the patient is first uploaded on device A, which takes *Tc*/2. Then he is imaged for *Ta* and finally he has to wait to get into device B until the previous patient has been downloaded and this takes another time *Tc*/2 as per our initial assumptions. In this case the time will be exactly like that developed in the formula for simultaneous imaging above Eq. 2e with $\mathrm{TX} = \mathrm{TL} + \mathrm{Tc} = \mathrm{Ta} + \mathrm{Tc} = \mathrm{Tb} + \mathrm{Tc}$
2. $\mathrm{Tb} + \mathrm{Tc}/2 \leq \mathrm{Ta}$. In this case, the patient in device B can be downloaded prior to the moment scan A is finished because imaging on device B is finished early. As a result device B is ready to take on the patient immediately. Then $\mathrm{TX} = \mathrm{TL} + \mathrm{Tc}/2$ (TL is the longer of Ta and Tb)
3. $\mathrm{Tb} \leq \mathrm{Ta} \leq \mathrm{Tb} + \mathrm{Tc}/2$. In this case $\mathrm{TL} + \mathrm{Tc}/2 \leq \mathrm{TX} \leq \mathrm{TL} + \mathrm{Tc}$ and the cost efficiency of the integrated system is somewhere in between cases 1 and 2.

It should be noted that type IIb system configurations are not restricted to PET/MR, but in principle equally applicable to PET/CT and SPECT/CT.

Results

Realistic assumptions on the cost of setting up and running the various cross-sectional imaging systems and some of their combinations are assembled in Table 2, where the grey fields are to be filled with the relevant parameters enumerated above. Table 2 incorporates Excel calculations of system costs per minute in euros for the following imaging devices: CT, MR, SPECT and PET as well as the integrated systems: PET/CT, SPECT/CT and PET/MR. The latter system costs are estimated for three configurations: sequential imaging systems in the same room (type IIa), separate rooms (type IIb) and for simultaneous systems (type III). The cost of type IIb systems is the sum of the cost of the individual devices plus the shuttle cost. Operating hours could be extended to reduce the scanning costs per minute. Note that shorter operating hours are assumed for nuclear equipment, particularly for systems involving PET, as the availability of radiopharmaceuticals is frequently limited.

In order to compare separate and integrated imaging, the scanning cost of an integrated system is subtracted from that of separate systems for a range of different configurations (Eq. 2c minus Eqs. 2d, 2e or 2f). A positive difference resulting from this operation indicates an operating cost advantage in favour of the integrated system, while a negative difference indicates an advantage for separately operated systems. Relevant factors for the outcome of the comparison are the respective imaging times, as well as the operating costs.

Figures 1 and 2 plot the cost difference for PET/CT and SPECT/CT as a function of the acquisition time of the slower system, while the other times are fixed at realistic values.

Integrated PET/CT and SPECT/CT, which are of type IIa configuration in the current technical implementations, show a cost advantage at imaging times below 12 and 3 min, respectively. The cost advantage range could potentially be extended to longer PET/SPECT imaging times, if a type IIb (systems in two rooms connected by a shuttle) configuration would be used. Figure 3 shows that a sequential (type IIa) PET/MR system with both devices in the same room cannot be run at a cost advantage for any MR imaging time with the assumed costs (line always below 0). A sequential (type IIb) PET/MR system with both devices in separate rooms shows a range of MR imaging times up to above 20 min for which integration has a cost advantage, while fully integrated (type III) PET/MR systems with simultaneous acquisition barely reach break-even for the cost numbers chosen. This happens when PET and MR imaging times are comparable.

Figures 4, 5 and 6 plot the cost difference for PET/CT, SPECT/CT and PET/MR as a function of the relative operating costs of the integrated system to the sum of the separate devices. PET/CT shows a cost advantage for the integration with relative costs smaller than 0.65–0.78. Realistic figures in Table 2 show that this ratio is 0.72 and thus within the range of realistic imaging and changing times in PET/CT. SPECT/CT shows a cost advantage for the integration with relative costs smaller than 0.54–0.78. Realistic figures in Table 2 show that this ratio is 0.78, i.e. barely within the range of realistic imaging and changing times in SPECT/CT. The highest relative costs of integrated to separate systems attaining breakeven occur with the shortest PET and SPECT imaging times of 12 and 10 min, respectively, and the longest changing times of 20 min at 0.78.

Sequential PET/MR shows a cost advantage for the integration with relative costs smaller than 0.6–0.74. According to the realistic figures of Table 2, the ratio is 0.93 for a one-room configuration and 1.03 for a two-room configuration. Simultaneous PET/MR shows a cost advan-

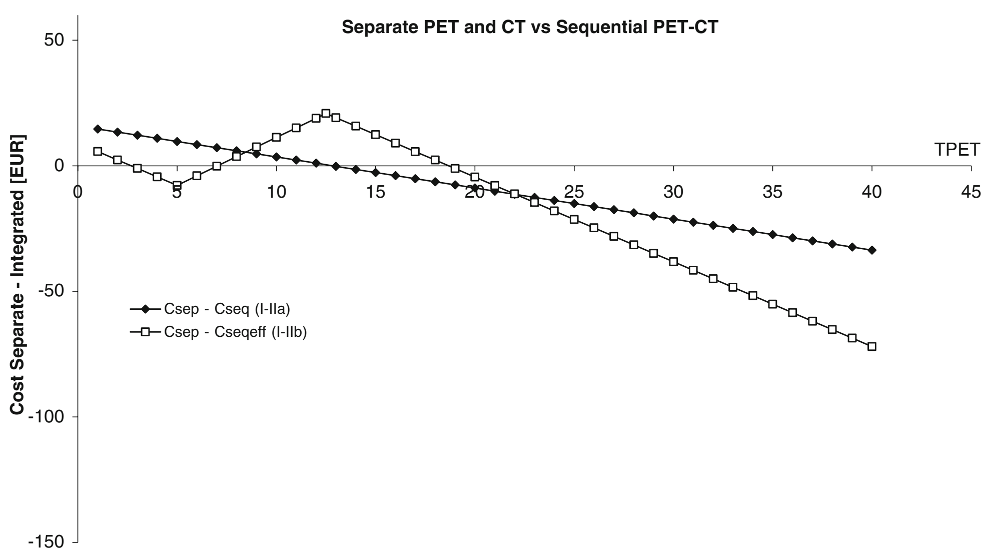


Fig. 1 Cost difference of separate and integrated systems for PET/CT as a function of the PET acquisition time. The changing time was fixed to 15 min and CT imaging time to 5 min. Both strictly sequential systems (one system waits while the other is scanning as with standard PET/CT) and sequential systems with a shuttle system which allows simultaneous operation are plotted. In principle two maxima occur when imaging time on one device equals imaging time plus download time on the other device. Only the maximum with TPET=12.5 min is seen in the PET/CT configuration

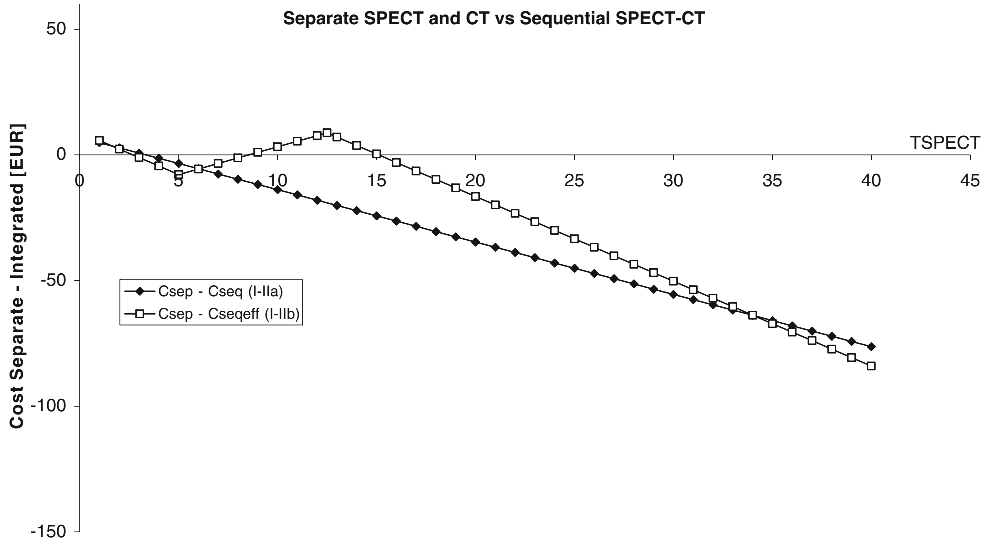


Fig. 2 Cost difference of separate and integrated systems for SPECT/CT as a function of the SPECT acquisition time. The changing time was fixed to 15 min and CT imaging time to 5 min. Like in Fig. 1, a hypothetical two-room SPECT/CT system could operate more effectively particularly when imaging time in one device equals imaging time plus download time in the second device

tage for the integration with relative costs smaller than 0.57–0.76 with realistic values being around 1.0 (Table 2). Hence, at current relative prices of integrated vs separate systems, a PET/MR configuration of type IIa and III cannot be built to be cost-efficient. Note that the cost difference for the most efficient sequential PET/MR configuration cannot be represented in Fig. 6 because the cost *cab* does not appear in Eq. 2f.

Discussion

The formulation of the equations and the calculations of the results of these equations for realistic numbers as presented in Table 2 and Figs. 1, 2, 3, 4, 5 and 6 permit one to obtain an overview of the key issues regarding cost and workflow of integrated imaging systems compared to separately operated devices.

The key factors favouring imaging system integration are:

- Only one patient changing time in integrated vs two patient changing times in separate imaging
- Lower cost of integrated system than cost of the sum of separate systems

while separate imaging systems are favoured by:

- Long imaging time relative to changing time and large difference between imaging times on the two devices

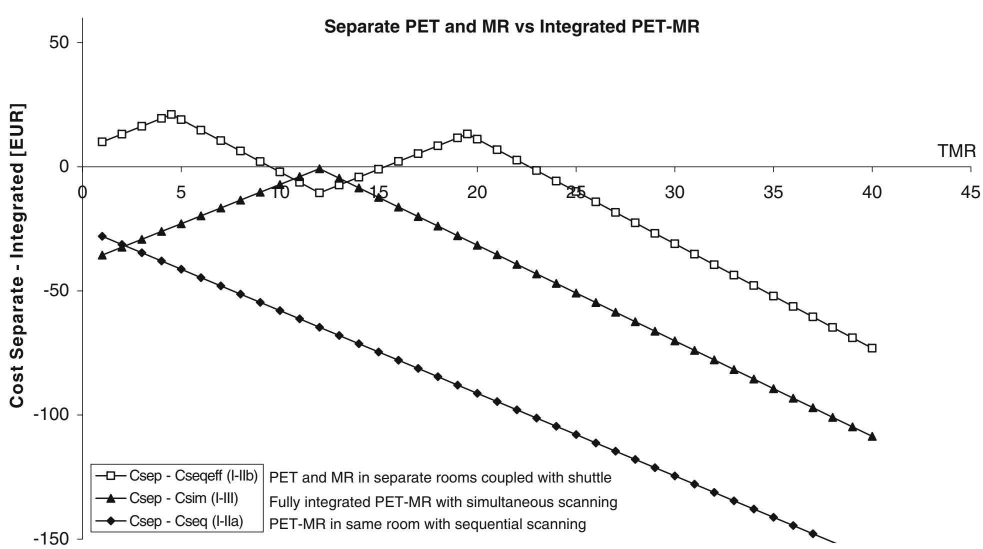


Fig. 3 Cost difference of separate and integrated systems for PET/MR as a function of the MR acquisition. The changing time was fixed to 15 and PET imaging time to 12 min. For the two-room "shuttle integrated" system the same comments apply as in Figs. 1 and 2

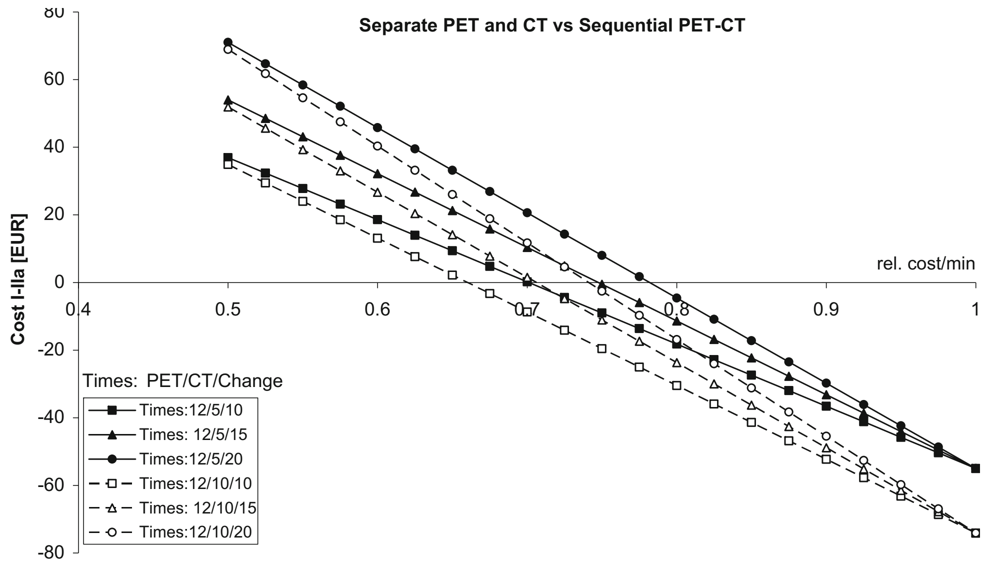


Fig. 4 Cost difference of separate and integrated PET/CT as a function of relative operation cost of the integrated PET/CT (cost of PET/CT divided by cost of separate PET plus separate CT). The cost difference is plotted for different potential timing combinations (PET: 12 min; CT: 5, 10 min; changing: 10, 15, 20 min)

– Cost of integrated system comparable or higher than the sum cost of separate systems

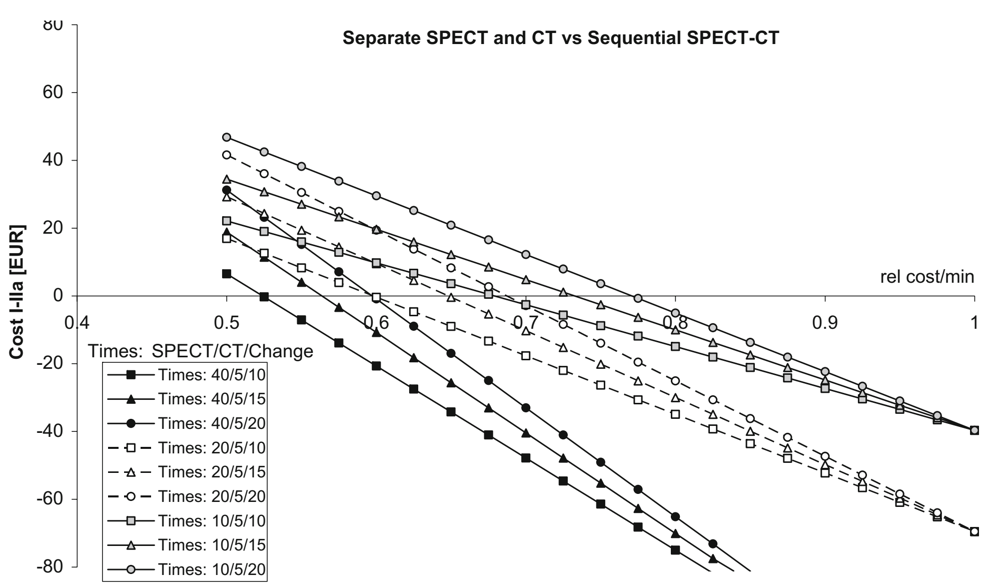
The relevant equation comparing the cost of separate minus integrated sequential one-room imaging is

Cost difference (separate vs integrated)

$$= \mathrm{Ta}^*(\mathrm{ca} - \mathrm{cab}) + \mathrm{Tb}^*(\mathrm{cb} - \mathrm{cab}) + \mathrm{Tc}^*(\mathrm{ca} + \mathrm{cb} - \mathrm{cab}), \quad (3)$$

where *ca* – *cab* is the slope with *Ta* representing PET, SPECT or MR imaging times in sequential PET/CT, SPECT/CT and PET/MR systems as shown by Figs. 1, 2 and 3, respectively. Together, the second and third terms represent the y-axis intercept. The slope (*ca* – *cab*) is always negative as seen in Figs. 1, 2 and 3 for the corresponding systems because the cost of a single device (*ca*) is always lower than that of an integrated system (*cab*). Hence, above certain values of imaging and changing times separate imaging is always less costly than integrated imaging. For PET/CT and SPECT/CT ranges of imaging parameters exist, where integrated imaging is less costly than separate imaging. In contrast, Fig. 3 shows that sequential mode PET/MR systems deployed in one room cannot be run in a cost advantageous range compared to separate imaging when reasonable cost data as given in

Fig. 5 Cost difference of separate and integrated SPECT/CT as a function of relative operation cost of the integrated SPECT/CT. The cost difference is plotted for different potential timing combinations (SPECT: 40, 20, 10 min; CT: 5, 10 min; changing: 10, 15, 20 min)



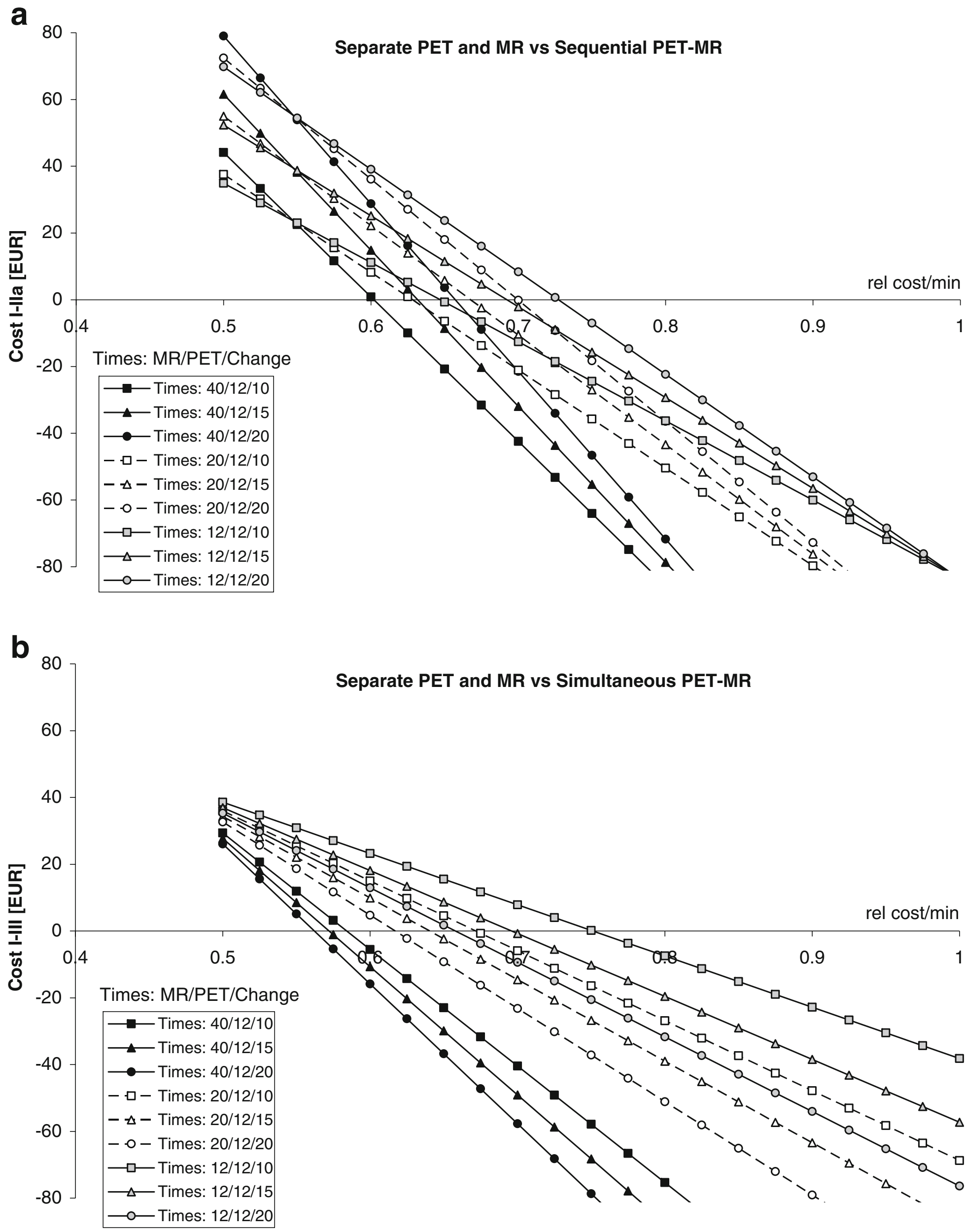


Fig. 6 Cost difference of separate and integrated PET/MR as a function of relative operation cost of the integrated PET/MR. **a** Sequential PET/MR. **b** Simultaneous PET/MR. The cost difference is plotted for different potential timing combinations (PET: 12 min; MR: 40, 20, 12 min; changing: 10, 15, 20 min). The actual relative cost according Table 2 is about 0.93 (one-room configuration) and 1.03 (two-room configuration) with **a** and 1.0 with **b**

Table 2 are used (negative y-axis intercept in Fig. 3). This supports the notion that sequential one-room imaging systems generally are not cost-effective solutions to integrated imaging.

To better understand why this is so, we look again at Eq. 3. It is noted that only the third term can become positive and it needs to be distinctly positive to offset the second term (*cb* – *cab*), which is negative by the same argument that *ca* – *cab* is negative. The second term in Eq. 3 above is weighted by the imaging time in the second system *Tb* (i.e. CT for PET/CT and SPECT/CT and PET in sequential PET/MR in Figs. 1, 2 and 3) and the third term by the patient changing time *Tc*. Thus, if the imaging time of the second system *Tb* is long compared to the changing time, integration is unlikely to offer a cost advantage. Likewise, if the integrated imaging system is of similar or higher cost than the separate devices (*ca* + *cb* vs *cab*), no operating range can be found where integration has a cost advantage compared to separate systems. While CT scanning is fast and in a range of 5 min which leads to a relatively small second term, PET imaging for partial body scanning currently is 10–15 min with some systems being as fast as 5 min. The range of positive values in Fig. 2 representing SPECT/CT imaging is very small and SPECT imaging would have to be performed in 3–5 min or less to achieve a cost advantage. This is not realistic with current Anger technology, but the advent of solid state-based cameras for cardiac imaging, where imaging times of 3–5 min are feasible [12], is good news: at least integrated SPECT/CT cardiac cameras can be run in a cost neutral range.

Separate room sequential and fully integrated systems require a special discussion as they perform better cost wise (Fig. 3). For fully integrated simultaneous PET/MR systems, the cost equations look more favourable than those of single-room sequential PET/MR systems, even though for realistic cost input data a cost advantage is not achievable according to Fig. 3. The maximum of the curve for such a system is reached when the imaging times for both exams is identical. If not, the difference in time is time during which one device is idling, which drives up the cost.

From a cost and workflow perspective, integrated sequential two-room PET/MR systems (and likewise PET/CT and SPECT/CT systems) are the most attractive, because both scanners can be used for scanning in parallel just like in the integrated simultaneous systems, except that when one device is scanning patient # *n*, the other already scans patient # *n*+1. In fact, this set-up is even more effective than simultaneous imaging and can be explained as follows. As MR imaging likely will take longer than PET imaging (or PET and SPECT imaging will take longer than CT imaging), patient # *n* can be downloaded from the PET scanner prior to when patient # *n*+1 has finished the MR scan (and in analogy this applies for CT vs PET or SPECT). Hence, the PET scanner (or CT scanner) is ready to receive the next patient immediately and without download time. With this set-up only upload on the MR system delays imaging and the patient changing time is reduced to $Tc/2$. As stated initially, reducing changing time always favours integrated imaging, as the integrated system spends less time idling and more time imaging. The curves in Figs. 1, 2 and 3 have two peaks which occur when the download time (half of the total changing time) is equal to the scan time difference for both devices in the integrated system. The insight that half of the changing time can be saved using a sequential two-room integrated system not only provides a cost advantage for such PET/MR systems than the other options, but also implies that PET/CT and SPECT/CT systems might be designed in this way and provide a cost advantage over current day systems. This may be particularly relevant in SPECT/CT integration.

Figures 4, 5 and 6 examine the range in which relative cost per minute of an integrated single-room system vs separate systems leads to a cost structure favouring system integration (+ range). If integrated systems cost as much as the sum cost of two separate systems (ratio 1), this is obviously never a favourable situation for system integration (Figs. 4, 5 and 6). Only when system integration results in substantially reduced cost compared to the sum cost of the two separate systems can integration have a cost advantage. The curves in Figs. 4, 5 and 6 explore a range of imaging and patient changing times, but all figures show that unless the running cost per minute of a combined system does not drop below 0.75–0.8, separate imaging is always more cost advantageous. While for PET/CT and SPECT/CT systems this is possible to attain, no important cost reductions of integrated vs separate PET and MR devices are manifest, and thus running an integrated PET/MR system at a cost advantage appears difficult. The reasons why this may be still possible with two-room sequential imaging systems were given above.

The presented analysis has several limitations, which were already partly enumerated when listing the model assumptions. Factors neglected supporting integration are synergy in personnel cost and the high utility of having hardware fused data available consistently leading to clinical benefits. Including this in our calculations is difficult because it is not clear how a price tag could be attached to this. Factors neglected which would further support separate imaging are that the patient shuttling time between the two examinations was neglected. As this is from several seconds to 2–3 min in the sequential systems, it still is substantially less than the overall changing time set at 10–15 min. The cost assumptions made to derive the figures in Table 2 may be subject to debate. First, amortization of equipment over 8 years is relatively long for some technologies such as CT. But if this is shortened it impacts the cost of the device as well as the integrated system and thus results in higher per minute cost on both sides of the equations. The same argument is true for building costs and capital cost.

For simplicity the cost of personnel was not included in the analysis using the assumption that the personnel needed for an integrated study is the same as that for performing two separate studies. This is probably not entirely true, but if anything, favours integrated exams as stated above. Finally, the fact that two systems deployed in two rooms are much more flexible because they can also be effectively used on patients who only need one of the two examinations has been ignored save for the analysis of sequential PET/MR systems deployed in two rooms.

Conclusion

In conclusion this analysis identifies the key factors differentiating workflow and cost advantages of integrated imaging vs imaging in two separate devices. They are the patient upload and download times and the cost reduction achieved in integrated systems vs two separate devices. The analysis suggests that PET/CT as currently operated can be run with a cost advantage compared to performing PET and CT separately on patients and SPECT/CT may have a cost advantage when new cadmium zinc telluride (CZT) SPECT systems are used. Integrated PET/MR will require complete integration for simultaneous measurements and substantial cost reductions for such fully integrated systems or a two-room shuttle integration strategy that the integrated systems operate at less cost than separate devices. The latter strategy may also lead to a new look particularly at SPECT/CT integration. This analysis ignores additional clinical value of providing hardware fused rather than software fused data, as it only focuses on workflow-cost issues.

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